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Review

Reflections on *Swift* from the early years

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ABSTRACT

The provenance of *Swift* lies with earlier discoveries of Gamma Ray Burst (GRB) phenomena, starting with the serendipitous discovery of GRBs by the Vela nuclear-test-ban-treaty monitoring satellites, through the first all sky GRB mapping by the *Compton Gamma-ray Observatory (CGRO)* to the discovery of X-ray afterglows by *BeppoSAX*. Building on these foundations, *Swift* has provided the astrophysics community with a new tool for studying GRBs; a rapid reaction spacecraft hosting a unique combination of newly available instrument technologies able to detect, locate and follow the life cycle of bursts across their energy spectrum from gamma-ray, through X-ray, to optical/UV. The *Swift* science team has shaped the scientific priorities for the mission and ensured access to world class observatories for rapid follow-up observations. Since launch, on 2004 November 20, *Swift* has been detecting GRBs at a rate of about 100 per year. Many of these have led to major breakthroughs in understanding GRB phenomena and are referenced here alongside comments on some of the events that at times threatened early demise of the *Swift* mission – happily averted through prompt action by the scientists and engineers of the mission operations team.

1. Provenance

At the start of the *Swift* era, Gamma Ray Bursts (GRBs) were already recognised as immensely powerful explosions originating at cosmological distances, whose outbursts persisted for durations ranging from milliseconds to tens of seconds or more. In these brief moments, the explosions radiate more energy than the Sun will release in its entire 10 billion year lifetime. Contemporary theories attributed these phenomena to the final collapse of a massive star, or the coalescence of a binary system induced by gravity wave emission.

GRBs were first discovered in the late 1960s (Klebesadel et al., 1973). Results from the *Compton Gamma-ray Observatory (CGRO)* showed them to be distributed isotropically over the sky occurring at a rate of about one per day over the eight year lifetime of the mission (Meegan et al., 1991). They come in two classes: long (>2 s), soft spectrum bursts and short, hard events (Kouveliotou et al., 1993). The *BeppoSAX* mission made the important discovery of X-ray afterglows associated with long bursts (Costa et al., 1997). Follow-up observations found afterglows at optical (van Paradijs et al., 1997) and radio (Frail et al., 1997) wavelengths and provided redshift (and hence distance) measurements to place upper bounds on the total energy ($>10^{51}$ erg) of the bursts. Identification of the hosts showed – at least for the small *BeppoSAX* sample – that long GRBs emanated from regions of high star formation rate in high redshift galaxies, thus providing clear confirmation of their extragalactic origin.

2. Opportunity

NASA's Announcement of Opportunity in 1998 of the competition for the next Medium Explorer Mission had been prefaced by strong public indications from the then NASA Administrator, Dr Dan Goldin, to the effect that NASA needed to solve the mysteries of the Gamma Ray Burst. Among the several proposals for GRB missions offered to NASA, the *Swift* proposal adroitly combined GRB expertise and *CGRO* heritage from NASA's Goddard Space Flight Center with X-ray astronomy expertise from Pennsylvania State University, adding European participation from the UK and Italy, from the University of Leicester (X-ray detectors), Mullard Space Science Laboratory (optical monitor), Osservatorio di Brera (X-ray optics) and the Italian Space Agency (mission operations). The *Swift* proposal was short-listed for selection in February 1999 and, on completion of a competitive Phase A mission study, was chosen as NASA's next MIDEX mission in September 1999.

Over the next 5 years, *Swift* was designed, built and tested, and was successfully launched from Cape Canaveral on a Delta 2 rocket on 2004 November 20.

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3. Mission

3.1. *Swift: the big ideas*

Five big ideas characterise the unique features of *Swift* (Gehrels et al., 2004). The *Swift* approach was, of course, motivated by the discovery of the GRB afterglow but needed to respond to the short-lived nature of the gamma-ray emissions. The Burst Alert Telescope (*BAT*) is a sensitive wide field gamma-ray imager, chosen to detect and determine the approximate position of new GRB outbursts. X-ray and optical/UV narrow-field telescopes provide accurate burst location and follow-up X-ray, optical and ultraviolet afterglow studies. The spacecraft provides a rapid autonomous repointing capability so, on detection of a new burst, *Swift* is commanded to slew, autonomously and rapidly (typically within 100 s), to point the X-ray (*XRT*) and the optical/ultraviolet (*UVOT*) telescopes at the *BAT*-determined burst position. As well as providing precise (arcsec) burst locations, the *XRT* and *UVOT* can establish whether X-ray/optical/UV emission is concurrent with, or delayed with respect to, the short-lived gamma-ray emission, and continue with extended observations of burst afterglows over days and weeks after the initial GRB detection. Prompt automatic notification of burst positions is provided to the *Swift* Science Data Centres via real-time data links between the spacecraft and the ground station. The GCN system notifies initial results to the extensive network of ground-based telescopes and other facilities supporting *Swift* for rapid multi-wavelength follow-up observations and host identification investigations of the newly observed bursts.

3.2. *Instruments*

The three scientific instruments on-board *Swift* together cover an energy range of ∼0.002–150 keV. The *BAT* detects gamma-rays using a coded-aperture instrument, combining high gamma-ray sensitivity with a 2 steradian field of view to cover about one sixth of the sky (Barthelmy et al., 2005). The *BAT* is able to determine initial positions of GRB emission to an accuracy of about 4 arcmin, within seconds of detecting the burst.

The resolution and sensitivity of the X-ray telescope and its CCD detectors are such that, after the spacecraft has repointed to a *BAT*-determined position and if an X-ray afterglow is found, burst locations are consistently refined to 5 arcsec or better typically within 100 s of the initial GRB detection (Burrows et al., 2005). Thereafter, *Swift* can re-visit the site of newly detected bursts over days and weeks with the *XRT* using its automatic mode-changing facility to follow afterglow decay or flaring over seven orders of magnitude in flux.

The *UVOT* is accurately aligned with the *XRT* and also makes use of *Swift*'s rapid slewing capability to search for optical and UV afterglow emissions from GRBs, especially those already detected in the *XRT* field of view (Roming et al., 2005). The resolution of the *UVOT* allows the location of detectable optical afterglows to an accuracy of 0.3 arcsec or better, allowing rapid identification of possible optical counterparts. Spectral discrimination is achieved using a range of five broadband spectral filters and two grisms (one optical, one UV), mounted on a wheel in front of the detector.

3.3. *Science team*

An essential aspect of the *Swift* mission is its ability to determine positions of hundreds of GRBs, as well as positions of transient sources detected during the sky survey, and to make these available rapidly through the GCN to enable the *Swift* science team and the wider scientific community to undertake ground-based and space-based multi-wavelength follow-up studies.

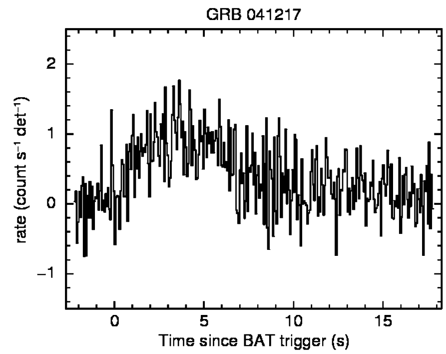

Fig. 1. *BAT* light curve of GRB 041217: the first detection of a GRB by *Swift*.

The *Swift* science team has collaborated closely with the project on follow-up observations with instruments ranging from robotic telescopes to some of the world's largest telescopes, and carrying out high-resolution spectroscopy, optical, IR, and radio monitoring of light curves, and morphological studies of host galaxies.

4. Early observations

4.1. *First BAT detection*

The first GRB trigger detected by *Swift*, GRB 041217, occurred on 2004 December 17 (Fig. 1; Palmer, 2004). Spacecraft commissioning was still going on: the *BAT* was the only instrument that had been activated, and autonomous spacecraft slewing had not yet been enabled. No afterglow emission was detected from an attempted ground-based observation. Nevertheless, *Swift* had seen its first GRB.

4.2. *First XRT afterglow*

On 2005 January 17, the *Swift-BAT* triggered and located GRB 050117. *Swift* responded autonomously to the *BAT* trigger, but repointing of the satellite was delayed by 193 s to avoid exposure of the *XRT* to the Earth's bright limb, by which time *Swift* had entered the high background region of the South Atlantic Anomaly and the consequent increase in the *XRT* background count rate levels. Because of these viewing and pointing constraints, such X-ray afterglow measurements as were obtained were rather sparse. Nevertheless, GRB 050117A does represent the first autonomous repointing of an X-ray telescope at a newly discovered GRB, in which simultaneous gamma-ray and X-ray flux measurements of the prompt emission were obtained and the transition from prompt emission to afterglow was observed (Hill et al., 2006).

GRB 050126 was the first GRB to which *Swift* was able to slew autonomously and immediately and detect a bright X-ray afterglow (Fig. 2), whose decay over three orders of magnitude was followed, over the subsequent 12 days (Goad et al., 2006). Ground-based follow-up identified an NIR afterglow providing the first detection of a host galaxy associated with a *Swift* burst, with a redshift $z = 1.29$ (Berger et al., 2005).

4.3. *First UVOT observation*

Commissioning the *UVOT* was a lengthy process determined by the need to protect the instrument automatically against accidental exposure to bright sources that might lie on spacecraft slew paths, such as the Sun, Earth, Moon, comets or bright stars. Consequently *UVOT* has a number of complex operating modes that required extensive testing before observations could begin.

GRB 050318 was the first GRB to be detected sequentially by the *BAT*, *XRT* and *UVOT* (Fig. 3). Following the *BAT* trigger, but after

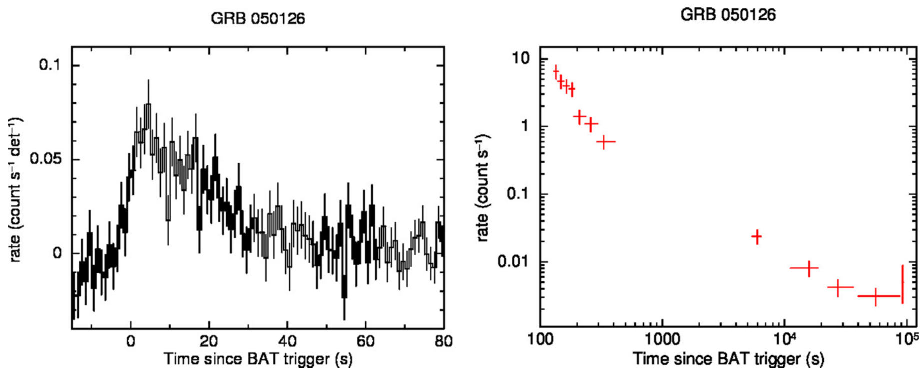

Fig. 2. *BAT* (left) and *XRT* (right) light curves of GRB 050126: the first GRB with a well-populated *XRT* light curve following an autonomous slew.

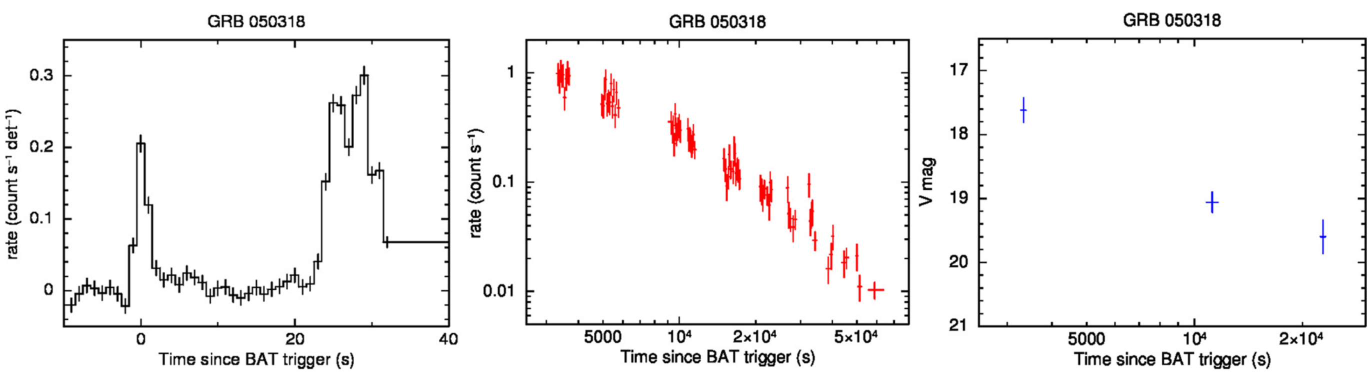

Fig. 3. *BAT* (left), *XRT* (middle) and *UVOT* (right) light curves of GRB 050318: the first *UVOT* detection of a burst.

a 30 minute delay caused by the Earth-limb observing constraint, *Swift* slewed autonomously, and detected a bright X-ray afterglow accompanied by magnitude <18 emission in the *UVOT* (Perri et al., 2005; Still et al., 2005). Ground-based optical observations with the Magellan/Bade telescope identified the host galaxy with redshift $z = 1.44$ (Berger and Mulchaey, 2005).

5. Early operations

A number of operational problems were encountered and resolved over the first couple of months as operations became progressively more routine. Each instrument was brought on stream and calibrated in sequence, with instrument calibration work fitted in between burst alerts and follow-up observations. Operations progressed from 24/7 to automated out-of-hours but with the duty scientists and operations team on call to deal with bursts or emergencies as required.

Spacecraft scheduling was dominated by the complexity of the pointing constraints which required avoidance of the Sun, Earth or Moon in the *XRT* and *UVOT* and high instrument background levels when the spacecraft was in transit through the SAA. This process became much more complex in the aftermath of a massive solar flare which occurred only 14 days into *Swift*'s orbital life – 2004 December 4.

At around 3 am local time, the spacecraft suddenly dropped into safe mode, but during recovery operations, it was noticed that power to the *XRT* CCD detector Peltier cooler could not be restored. The *UVOT* team also reported unusual anomalies. Further investigation revealed that the Peltier power unit had failed beyond recovery, believed to be due to a particle impact during the flare. As a consequence the *XRT* CCD could no longer be maintained at its design temperature of $-100\,^{\circ}$C and large orbital variations in CCD temperature resulted due to Earth albedo warming of the *XRT* passive radiator. For large parts of the orbit, high levels of detector thermal noise rendered the *XRT* unable to perform its function.

Solutions were found by analysing the orbital evolution of the thermal load on the *XRT* radiator from Earth albedo emission and then adding new pointing constraints to the scheduling software such as to minimise the Earth view of the *XRT* radiator and keep the CCD detector cooled to around $-52\,^{\circ}$C or below. A totally new pointing strategy was developed, tested and implemented within two weeks of the incident, with a solution that remains in operation 10 years later.

6. Early highlights

6.1. Short GRBs

Swift's discovery of the first afterglows from short, hard GRBs [GRB 050509B (Gehrels et al., 2005), GRB 050724 (Campana et al., 2006a), together with the HETE burst GRB 050709 (Fox et al., 2005)] was followed by a systematic study through X-ray, optical and radio afterglows measurements of multiple short bursts (Fox and Roming, 2007; Barthelmy, 2007, and references therein) (see also Fig. 4). Their distance scale ($z > 0.1$) and energetics ($E > 10^{48}$ erg) have been established, and they have been revealed definitively as a cosmological phenomenon. The short bursts have been found among old stellar populations – in elliptical galaxies, galaxy clusters and the outskirts of younger galaxies. The absence of associated supernovae appears to rule out an origin in the deaths of massive stars, in contrast to the now-accepted view of the origins of long-duration gamma-ray bursts, whose host galaxies, redshifts, and associated supernovae are all consistent with the collapsar-supernova model. Instead the observed properties of short bursts point to coalescence of a compact-object binary, either neutron star–neutron star or neutron star–black hole (King, 2007), enabling the prospects for gravitational-wave detection to be reassessed (Hough, 2007).

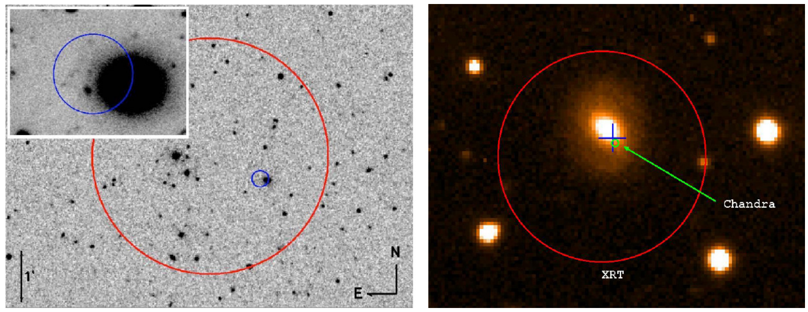

Fig. 4. Left: The first short burst afterglow localised by *Swift*: GRB 050509B. The large circle shows the *BAT* position error, while the smaller circle shows the *XRT* position uncertainty. Reproduced from Gehrels et al. (2005). **Right**: The short burst GRB 050724. The precise *Chandra* localisation is shown inside the *XRT* error circle. Credit: Gianpiero Tagliaferri/Osservatorio Astronomico di Brera. In both cases, the extended source overlapping the X-ray position is an elliptical galaxy.

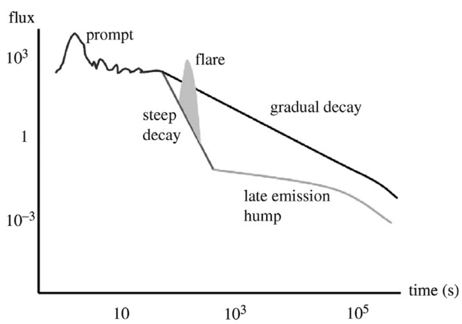

Fig. 5. A schematic view of the early GRB X-ray light curve. Following the prompt emission, which typically lasts a few 10s of seconds, the decay tends to follow one of two paths: (i) a steep decay, during which the flux can fall by several orders of magnitude, followed by a shallower, "late emission hump" starting at $\sim 10^3$ s; or (ii) a more gradual decay. Either decay path can end with a break at $>10^4$ s to a steeper decay. X-ray flares can occur during either decay path, most prominently during the first hour. Figure taken from O'Brien and Willingale (2007).

6.2. High redshift GRBs

In its first year, *Swift* located more high redshift ($z > 2$) bursts than any other mission. The majority of *Swift* GRB detections were of the long burst variety, and studies of the early afterglows, previously inaccessible, have added to evidence supporting the view that long duration bursts are produced during the collapse of a massive star. Within the first year, redshifts were measured for over 50 long bursts, including the highest recorded redshift at the time ($z > 6$) of GRB 050904 (Kawai et al., 2005; Cusumano et al., 2007).

This record has been surpassed several times since. Currently GRB 090423, with a spectroscopic redshift of ~ 8.2 (Tanvir et al., 2009; Salvaterra et al., 2009), and GRB 090429B, with a photometric redshift of ~ 9.4 (Cucchiara et al., 2011), are the most distant bursts to have been observed by *Swift*.

6.3. Afterglows

Swift has filled the temporal gap between the prompt emission and the afterglow that earlier missions were generally unable to probe. O'Brien et al. (2006) and O'Brien and Willingale (2007) have shown that combined light curves from the *BAT* and the *XRT* show an essentially smooth transition between the non-thermal prompt X-ray emission and the decaying X-ray afterglow. They and others (Piran and Fan, 2007; Panaitescu, 2007; Burrows et al., 2007, and references therein) agree on a description of the generic nature of early GRB light curves, illustrated in Fig. 5, with the proviso that not all phases in the afterglow evolution shown in the figure are present in all bursts and suggesting that several emission processes may be involved.

When present as the dominant feature, the initial steep decay is attributed to large angle "high latitude" emission produced during the burst while the central engine remains active; when the slower unbroken power law decay is dominant, this is attributed to forward shock emission from a narrow jet. Most bursts appear to exhibit a combination of both processes. Many afterglows have X-ray flares superimposed on the broken power law curve, illustrated in Fig. 5, also indicative of continuing activity within the central engine for extended periods after the initial outburst (Burrows et al., 2007).

6.4. SNR breakout

Swift's multi-wavelength measurements (gamma-ray to optical/UV) of the exceptional nearby burst GRB 060218 ($z = 0.033$) provided a direct observation of the shock breakout in the supernova collapse of SN 2006aj (Campana et al., 2006b; Blustin, 2007; Zhang et al., 2007). As Fig. 6 shows, the gamma-ray emission lasted for 35 min, longer and softer than any previous burst, whilst the X-ray afterglow exhibited flat emission for ~ 3000 s, after which the light curve followed a GRB fireball-like decay associated with high latitude emission from internal shocks followed by jet expansion into the local environment. UV afterglow emission, seen with *UVOT* over the first two days, then became swamped by late brightening of optical emission over the next 20 days, symptomatic of SN emission, later correlated with ground based observations and redshift determination of SN 2006aj.

GRB 060218/SN 2006aj provoked a massive global programme of ground-based observations which followed the evolution of the SN emission after the *Swift*-observed shock breakout. Spectroscopy of narrow emission lines enabled unambiguous determination of the redshift; continuum and broad absorption features characteristic of Type 1c supernovae were found and many small telescopes were used for bolometric mapping. Marshalling observations of this particular burst, using telescopes from all around the world, was a spectacular example of the much wider role undertaken by the *Swift* science team in their support of *Swift* GRB discoveries through use of extensive ground-based follow-on observations.

7. Conclusions

This paper is very much a personal reflection on the events, discoveries and achievements realised in the first year or so of *Swift*'s life in orbit after the previous five years of intense technological preparation. More complete accounts of results from that early period are to be found in the collection of papers from the first *Swift* conferences, that took place in 2005 and 2006; in Washington (Holt et al., 2006), at the Royal Society in London (Wells et al., 2007) and in Venice (Chincarini et al., 2006). This conference, *Swift: 10 Years of Discovery*, builds on the legacy of GRB science

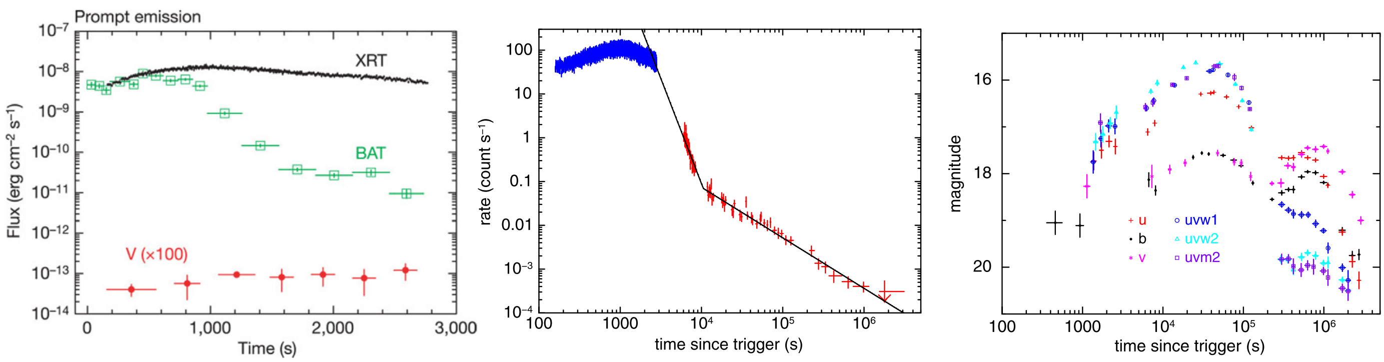

Fig. 6. Left: The early *Swift* gamma-ray, X-ray and UV emission of GRB 060218. Figure reproduced from Campana et al. (2006b). **Middle**: Full *Swift*-XRT light-curve, with a fit to the later-time decay. **Right**: *Swift*-UVOT light-curve, showing the decaying GRB optical/UV emission is swamped by the late brightening characteristic of supernova emission.

that these early conferences established, but the scope is greatly extended to include multi-wavelength and temporal studies of an impressively wide range of astronomical targets ranging from the most distant galaxies, transient objects to nearby comets. Such is the versatility and the resilience of the spacecraft, the instruments and the operational facilities 10 years on, that the subject remains as fresh and exciting as we recall it from the early days.

Acknowledgments

Many individuals and groups have made outstanding contributions to *Swift*'s success and have earned our gratitude. But special congratulations and thanks on this anniversary occasion are due to Neil Gehrels, for his foresight and leadership from 1998 onwards, in bringing *Swift* into being and steering it to its many successes. AW wishes to thank Dr Kim Page for her assistance with the preparation of this paper, and to acknowledge his election as Emeritus Professor at the University of Leicester in 2005 and award of his Leverhulme Emeritus Fellowship that allowed him to experience the enjoyment and satisfaction of being part of *Swift* in the early years.

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